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Experiments on the Diffusion of Smoke in Isotropic Turbulent Flow

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Detailed properties of the downstream evolution of smoke released in an isotropic turbulent flowfield are reported. Effects of turbulence on the mass-transfer characteristics of the flow, which in turn affect such things as the spread of pollution and the rate of chemical reactions, are studied. Smoke is released a short distance downstream of a uniform grid placed perpendicular to a uniform stream of air in a wind tunnel. A laser Doppler velocimeter is used to make the desired velocity field measurements, and a laser light-scatttering technique provides the "instantaneous" mass fraction c of smoke at the same point in the flowfield. One-point statistical properties of the velocity and concentration fields are obtained. The one-point cross correlations $\overline{cu}$ and $\overline{cv}$ are also reported.

I. Introduction

THE understanding of the process of diffusion of contaminants in turbulent shear flows is basic to the understanding of many physical processes. The turbulence strongly affects the mass-transfer characteristics of the flow, which in turn strongly affects such things as the spread of pollution and the rate of chemical reactions. Little experimental research relevant to these studies has been done due to the difficulties in measuring particulate concentration on a real-time basis, remotely, with high spatial resolution. The present work has demonstrated the feasibility of measuring not only the concentration of the particles and their velocities, but also velocity-concentration covariance functions.

In the past, several methods have been used for making concentration measurements. One of the earliest ways assumes that the diffusion of heat and particulate contaminants are analogous. Experiments[1-8] were conducted using a fine heated wire to "tag" the fluid and measurements were made of temperature fluctuations downstream. It has been pointed out, however, that the diffusion of heat and particles can be quite different,[9] depending on the particle characteristics, so that applications of the results obtained from the diffusion of heat to the diffusion of particles may be misleading[10] if particle characteristics are not carefully accounted for. The hot-wire anemometer has been used to measure concentration fluctuations in mixtures of two gases.[11-14] Several techniques using light have been used for making particulate concentration measurements. One of these[15] uses fiber optics to bring light into the fluid—allowing it to pass through a small volume of the fluid—then measuring either the absorption or scattering of the light to get the concentration. This technique has two major drawbacks compared to the present technique: first, it introduces a probe into the flow and hence disturbs it; second, it does not permit simultaneous measurement of the local velocity. Another technique[16-20] using light measures light scattered from a sheet or beam of light in a manner similar to that proposed here. The earlier work used a high-intensity vapor or arc light as its source. Another method[21] for investigating the motion of small particles is to take a series of photographs and infer the motion of the particles from their displacement on successive frames.

Shaughnessy and Morton[22,23] carried the light-scattering method a step forward by using an argon-ion laser as a light source. This light source gives improved spatial resolution and improved signal-to-noise ratio. For a complete discussion of the system see Refs. 22 and 23. As pointed out in these references, it is extremely difficult to measure absolute concentrations. In fact, for our purposes here, relative concentrations are all that are required. The coherent nature of the laser radiation makes it possible to simultaneously measure the local velocity using laser Doppler techniques.[24-26] The present work gives preliminary experimental results of the diffusion from a "point" source of smoke in grid turbulence, including the velocity-concentration correlations $\overline{cu}$ and $\overline{cv}$, where u and v are the axial and radial velocity components, respectively. Diffusion of the "small" smoke particles used in the present experiment is expected to be similar to diffusion of heat.

II. Experimental Arrangement

The downstream evolution of smoke released in an isotropic turbulent flowfield is studied experimentally. Figure 1 shows the experimental arrangement. Air flows uniformly in the test section of the 20×30-cm wind tunnel. A uniform biplanar grid having a rod diameter of 2.4 mm and a mesh-length of 12 mm is placed perpendicular to the flow and smoke is released 13 mm downstream of the grid center. The diameter of the smoke-releasing jet is 6 mm. Practical considerations necessitated a large release velocity (10 m/s), compared to a tunnel speed of 4 m/s. The tunnel velocity is limited by the maximum speed of the fan, while large release velocity is necessary to supply enough smoke particles for a prescribed signal-to-noise ratio. However, 10 mesh-lengths downstream from the grid, jet speed is essentially equal to tunnel speed; this is used as the first measuring station. An ideal arrangement for this experiment would be a "point" source of smoke which does not add any momentum to the airstream.

The smoke used is dioctal phthalate polydisperse produced by a Royco smoke generator. The mean particle diameter given in the specifications is 0.3 μ.

Measurements of both concentration and velocity fluctuations at a point are of interest. The probe used is a laser anemometer capable of measuring "instantaneous" concentration and velocity component in any direction at the same point in the flowfield without disturbing the flow. As

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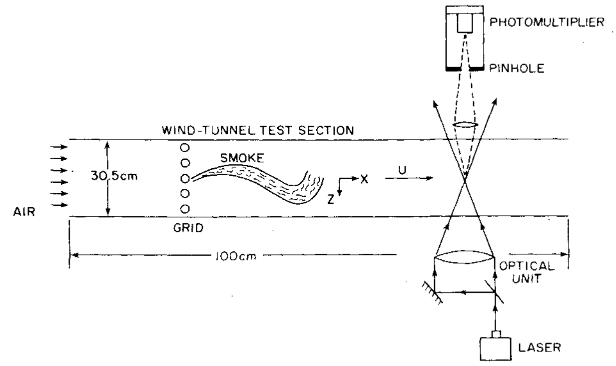

Fig. 1 Schematic of wind-tunnel and optical arrangement.

shown in Fig. 1, the laser anemometer is used in the differential Doppler mode on forward-scattered light. The two beams are of equal intensity, forming a fringe system in the intersection volume. Scattered light is picked up over a wide angle since the differential Doppler frequency is independent of the direction of detection.

The spatial filter used to select light scattered from the intersection volume consists of a lens and a 1-mm-diam pinhole. The laser beam diameter is 0.1 mm at the intersection point, and the lens is located halfway between the control volume and the pinhole, at twice the focal length from either, to give unit magnification. Thus, the control volume dimensions are defined by the beam and aperture diameters. The spatial resolution of the system is about 2 mm.

The photomultiplier high-voltage supply is varied to yield maximum signal-to-noise ratio. The signal-to-noise ratios achieved were usually greater than 100 for the axial velocity signal and 200 for the concentration signal. The radial velocity measurements are considerably more difficult and the signal-to-noise ratio then is about 20. The output of the PM-tube is amplified and low-pass filtered at 5 kHz to give a voltage directly proportional to the concentration c of smoke.[22,23] For velocity measurements, the output is band-pass filtered between 300 kHz and 3 MHz, amplified, and fed to a circuit which removes amplitude information. The frequency-modulated signal is then fed to a phase locked-loop processor which demodulates it and changes the Doppler shift in frequency to a fluctuating voltage output directly proportional to the velocity component in the desired direction. The phase-locked loop is capable of following $\pm 40\%$ velocity fluctuations, and works well in intermittent flows such as the present one.[26]

The velocity-measuring capability was compared along the centerline with both a pitot tube and a hot-wire anemometer (the hot wire was operated with clean air replacing the smoke). The maximum difference in mean velocity among the three probes was 3%. The turbulent intensities were compared between the laser system and the hot wire, yielding a maximum difference of 10%. Earlier work[26] indicates that the laser system yields relatively accurate mean velocities and turbulent intensities even when the flow is highly intermittent. It should be pointed out, however, that the laser system can measure velocities only where smoke is present. Thus, in the highly intermittent regions, turbulent intensities are not as accurate as when smoke is always present. This, however, does not affect the accuracy of $\overline{uc}$, since $c=0$ when u is in error.

Profiles are taken 10-45 mesh-lengths downstream of the grid. This is 20-90 jet diameters from the smoke source, and corresponds to the region where smoke-release velocity is undetectable. The main quantities to be measured to document the velocity and concentration fields are the mean velocity, rms velocity fluctuations, mean concentration, rms concentrations, concentration autocorrelation functions, spectra, scales, intermittencies, probability distributions, and

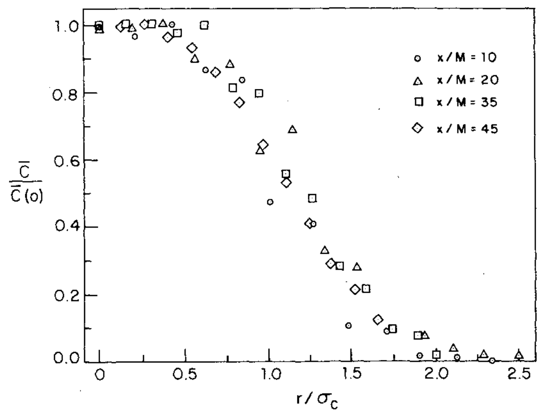

Fig. 2 Mean concentration profiles at different downstream locations.

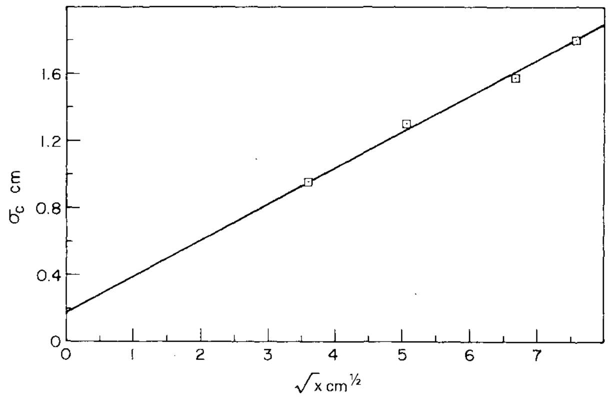

Fig. 3 Standard deviation of the mean concentration profiles.

concentration-velocity correlations. The concentration-velocity correlations are of particular importance, since they appear in all the (heuristic) mixing length theories. There are apparently very few measurements of these quantities available.[1,2,14,26]

The correlation functions, probability distributions, and intermitencies are measured using a Federal Scientific Ubiquitous Correlator model UC-202B. Spectra are obtained from the Fourier transform of the corresponding auto-correlation functions. The intermittencies were measured using the cumulative probability mode and were measured as the probability that the concentration signal exceeded the noise level in the instrument.

III. Experimental Results

The characteristics of the background flow—i.e., the degree of isotropy, the rate of decay of turbulence kinetic energy, etc.—were determined and found to compare well with grid turbulence generated in other wind tunnels. Turbulence level is about 8% at 10 mesh-lengths downstream of the grid, decaying to about 3.5% at 45-mesh lengths downstream of the grid.The exponent of decay[9] computed from the present data is about 1.1, indicating typical rate of decay of turbulent kinetic energy generated behind a grid. More complete documentation of the background flow is available elsewhere.[27]

Mean concentration profiles at different downstream locations are shown in Fig. 2. The radius of the mixing region is normalized with the dispersion length-scale (standard deviation of mean concentration profile). The profiles are nearly Gaussian and similar and are consistent with the theoretical prediction of self-preservation for a point source of a contaminant in an isotropic turbulent flowfield.[9,28] The profiles are slightly higher than Gaussian for $r/\sigma_c<0.5$ and lower than Gaussian for $r/\sigma_c>0.5$.

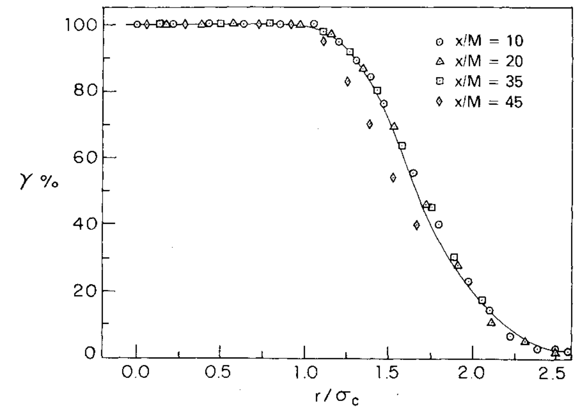

Fig. 4 Concentration intermittency profiles.

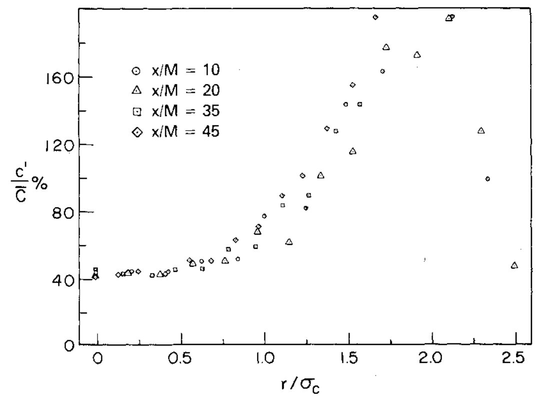

Fig. 5 Concentration fluctuations.

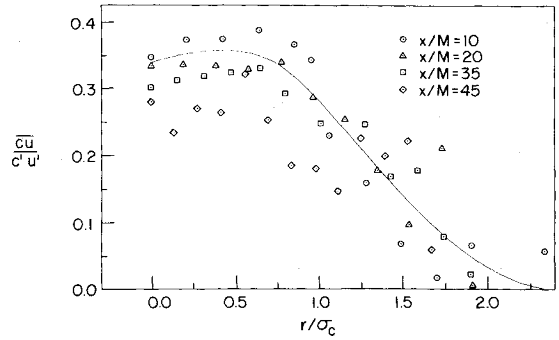

Fig. 6 Velocity-concentration correlation.

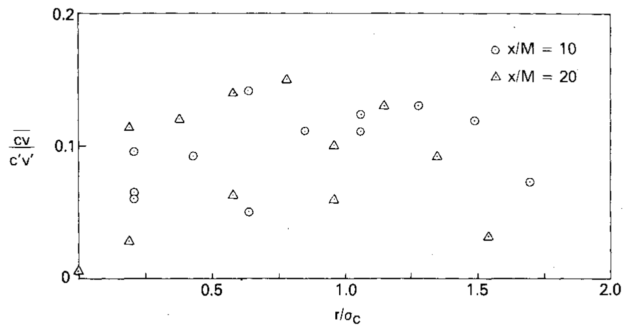

Fig. 7 Velocity-concentration correlation.

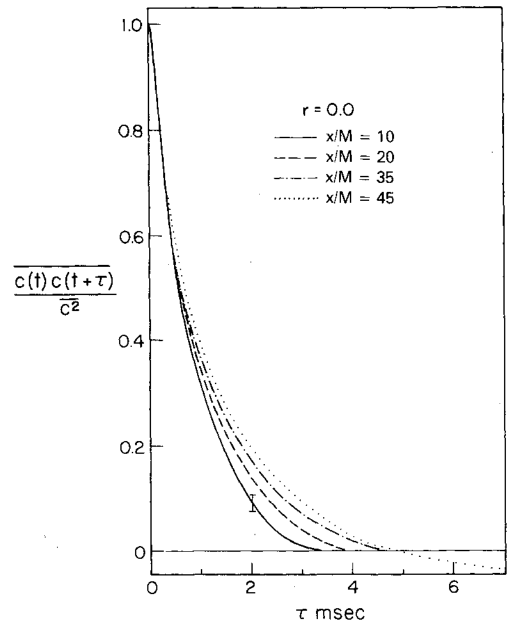

Fig. 8 Concentration autocorrelation.

The growth of the dispersion length-scale is shown in Fig. 3. It grows linearly with the square root of time (or distance from the grid), indicating long time-range dispersion, as predicted theoretically. This also agrees with previous experimental results[6,7] for the dispersion of a contaminant (heat) released from a line source in grid turbulence. In the present experiments, diffusion of the smoke particles used (0.3 μ diameter) is expected to be quite similar to diffusion of heat. The relaxation time required for those particles to adjust to a changing flow is of the order of a microsecond, much less than the turbulence time scales found in the present flowfield.

Concentration intermittency profiles are shown in Fig. 4. This intermittency is defined as the percentage of time the concentration signal is nonzero. It is calculated by determining the probability that the light level at the detector exceeds the noise level. The flow, as expected, is highly intermittent, which makes measurements rather difficult. The profiles are generally similar to the ones observed in other intermittent flowfields.[22,23]

The concentration fluctuation intensities are shown in Fig. 5 for different downstream locations. These profiles are similar and consistent with the self-preservation hypothesis since they are plotted vs r/σ_c, although data scatter is slightly more pronounced. Fluctuations as high as 200% are attained at the outer edges of the mixing region. Correcting for intermittency, however, reduces that to about 120%. The maximum level occurs at about two standard deviations from the center.

Figure 6 shows the downstream evolution of the velocity-concentration correction $\overline{cu}$, where u is the axial velocity component. The data scatter is pronounced, but general trends of the profiles are still apparent. The faired curve is drawn simply to help the reader follow the general trends of the data points. Thus, the curve should not be construed to have any strict mathematical genesis. The correlation is positive, and its maximum value is about 0.35 at about one-half standard deviation from the centerline of the mixing region. At about two standard deviations, the correlation approaches zero. Positive velocity fluctuations are associated, on the average, with positive concentration fluctuations, which indicates transfer of smoke from high-concentration regions (near the center) to low ones (near the outer edges). This, perhaps, is due to the fact that the smoke is introduced with a positive velocity increment; thus, high c corresponds to high u. Previous data for comparison are scarce and most of the available ones are for different flowfields.[1,3,14,26] It should be noted that near the edges of the mixing region velocity measurements are rather inaccurate due to the lack of a sufficient number of smoke particles in this highly intermittent region.

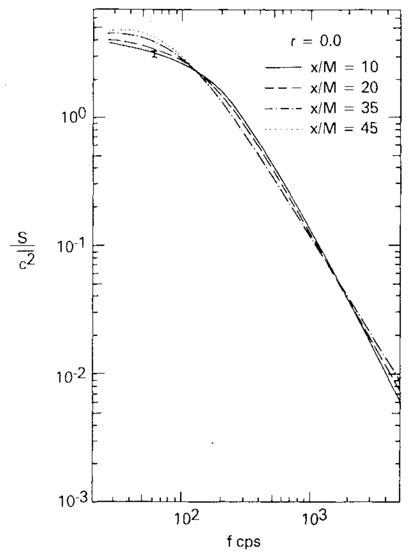

Fig. 9 Concentration spectra.

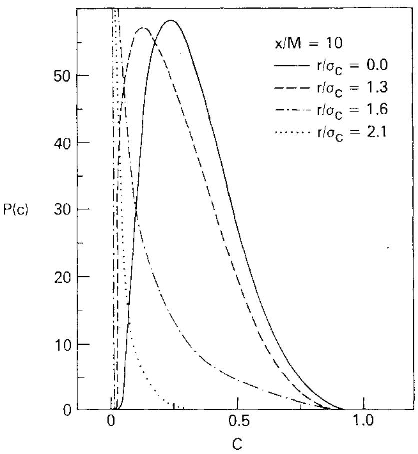

Fig. 10 Concentration probability distribution.

The radial velocity component v is much harder to measure than the axial component u. The optical unit is rotated 45 deg to measure $u+v$, then it is rotated -45 deg to measure $u-v$; thus, by adding and subtracting the two signals, u and v could be obtained in a way similar to the one employed in an X-array hot wire.[9] The velocity-concentration correlation $\overline{cv}$ is shown in Fig. 7 for $X/M=10$ and 20 only. The measurements further downstream of the grid are highly scattered and are not shown. The maximum value of the correlation coefficient is about 0.14, less than half the maximum value of $cu/c'u'$. The scatter in $\overline{cv}$ data is pronounced, and a different optical setup should be used to measure $(u+v)$ and $(u-v)$ simultaneously, thus reducing the drift effects.

Figure 8 shows the concentration autocorrelation coefficient. The area under each curve is the integral time (or length) scale and, as expected, is increasing downstream. The correlation shows a definite negative region for $X/M=45$ only.

Figure 9 shows the spectrum, or the Fourier transform of the autocorrelation coefficient, of the concentration signal. The spectrum is normalized to yield a unit area under each curve. Differences between the different spectra are small indeed. The concentration spectra exhibit a region of $-5/3$ slope; however, that does not necessarily indicate the existence of an inertial subrange for the moderate turbulence Reynolds numbers encountered in this experiment (about 100, based upon typical rms velocity fluctuations and a corresponding Taylor microscale).

Figure 10 shows the probability distribution for the concentration signal at different distances from the centerline of the mixing region, 10 mesh-lengths from the grid. As previously observed,[14] the probability density is highly skewed and non-Gaussian. This is due to the fact that concentration is bounded between zero (pure air) and unity (pure smoke).

IV. Concluding Remarks

Dispersion and detailed properties of the downstream evolution of smoke released in an isotropic turbulent flowfield are reported. A laser Doppler velocimeter is used to make the desired velocity field measurements, and a laser light-scattering technique provides the "instantaneous" mass fraction c of smoke at the same point in the flowfield. One-point statistical properties of the velocity and concentration fields are obtained.

The present flow configuration—grid turbulence with smoke "leaked" through a hole in the grid—is of great interest since it is the simplest possible diffusion problem. The mean-concentration profiles are Gaussian and self-preserved as predicted theoretically. The dispersion length scale grows linearly with the square root of time. The velocity-concentration correlation coefficients $cu/c'u'$ and $cv/c'v'$ are positive and have maximum values of about 0.35 and 0.14, respectively. The scatter in cv data is pronounced, and a different optical setup should be used to measure $(u+v)$ and $(u-v)$ simultaneously, thus reducing the drift effects. Some (heuristic) mixing length models for the diffusion process could be developed using the present data. While models of this sort have little theoretical basis, they have proven to be useful in many engineering applications.

Acknowledgment

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References

[1] Corrsin, S. and Uberoi, M. S., "Further Experiments on the Flow and Heat Transfer in a Heated Turbulent Air Jet," NACA Rept. 998, 1950.

[2] Uberoi, M. S. and Corrsin, S., "Diffusion of Heat from a Line Source in Isotropic Turbulence," NACA Rept. 1142, 1953.

[3] Mills, R. R., Kistler, A. L., O'Brien, V., and Corrsin, S., "Turbulence and Temperature Fluctuations Behind a Heated Grid," NACA Tech. Note 4288, Aug. 1958.

[4] Mills, R. R. and Corrsin, S., "Effect of Contraction on Turbulence and Temperature Fluctuations Generated by a Warm Grid," NASA Memo. 5559W, May 1959.

[5] Wiskind, H. K., "A Uniform Gradient Turbulent Transport Experiment," *Journal of Geophysical Research*, Vol. 67, July 1962, pp. 3033-3048.

[6] Shlien, D. J., "Dispersion Measurements of a Fluid Sheet in Two Turbulent Flows," Ph.D. dissertation, The Johns Hopkins University, 1971.

[7] Shlien, D. J. and Corrsin, S., "A Measurement of Lagrangian Velocity Autocorrelation in Approximately Isotropic Turbulence," *Journal of Fluid Mechanics*, Vol. 62, Jan. 1974, pp. 255-271.

[8] Wigeland, R. A. and Nagib, H. M., "Diffusion from a Periodically Heated Line Source Segment and its Application to Measurements in Turbulent Flows," *Turbulent Mixing in Nonreactive and Reactive Flows*, edited by S. N. Murthy, Plenum Press, New York, 1975, pp. 417-424.

[9] Hinze, J. O., *Turbulence*, 2nd Ed., McGraw Hill, New York, 1975.

[10] Kennedy, D. A., "Some Measurements of the Dispersion of Spheres in a Turbulent Flow," Ph.D. dissertation, The Johns Hopkins University, 1965.

[11] Corrsin, S., "Extended Applications of the Hot-Wire Anemometer," NACA Tech. Note 1864, 1949.

[12] Way, J. and Libby, P. A., "Hot-Wire Probes for Measuring Velocity and Concentration in Helium-Air Mixtures," *AIAA Journal*, Vol. 8, May 1970, pp. 976-978.

[13]Way, J. and Libby, P. A., "Application of Hot-Wire Anemometry and Digital Techniques to Measurements in a Turbulent Helium Jet," *AIAA Journal*, Vol. 9, Aug. 1971, pp. 1567-1573.

[14]Stanford, R. A. and Libby, P. A., "Further Applications of Hot-Wire Anemometry to Turbulence Measurements in Helium-Air Mixtures," *The Physics of Fluids*, Vol. 17, July 1974, pp. 1353-1361.

[15]Yang, B. T., "Study of Turbulent Diffusion from a Ground Released Puff by a Laser Light-Scattering Method," Ph.D. dissertation, Colorado State University, 1972.

[16]Becker, H. A., Hottel, H. C., and Williams, G. C., "On the Light-Scatter Technique for the Study of Turbulence and Mixing," *Journal of Fluid Mechanics*, Vol. 30, Nov. 1967, pp. 259-284.

[17]Becker, H. A., Hottel, H. C., and Williams, G. C., "The Nozzle-Fluid Concentration Field of the Round, Turbulent, Free Jet," *Journal of Fluid Mechanics*, Vol. 30, Nov. 1967, pp. 285-303.

[18]Becker, H. A., Rosensweig, R. E., and Gwozdz, J. R., "Turbulent Dispersion in a Pipe Flow," *A.I.Ch.E. Journal*, Vol. 12, Sept. 1966, pp. 964-972.

[19]Nye, J. O. and Brodkey, R. S., "The Scalar Spectrum in the Viscous-Convective Subrange," *Journal of Fluid Mechanics*, Vol. 29, July 1967, pp. 151-163.

[20]Schneiderman, A. M. and Sutton, G. W., "Laser Planogram Measurements of Turbulent Mixing Statistics in the Near Wake of a Supersonic Cone," *The Physics of Fluids*, Vol. 13, July 1970, pp. 1679-1682.

[21]Snyder, W. H. and Lumley, J. L., "Some Measurements of Particle Velocity Autocorrelation Functions in a Tubulent Flow," *Journal of Fluid Mechanics*, Vol. 48, July 1971, pp. 41-71.

[22]Shaughnessy, E. J., "Measurement of a Particle Diffusion in a Turbulent Jet by Laser Light-Scattering," Ph.D. dissertation, University of Virginia, 1975.

[23]Shaughnessy, E. J. and Morton, J. B., "Laser Light-Scattering Measurement of Particle Concentration in a Turbulent Jet," *Journal of Fluid Mechanics*, Vol. 8, April 1977, pp. 129-148.

[24]Durst, F., Melling, A., and Whitelaw, J. H., "Laser Anemometry: A Report on EUROMECH 36," *Journal of Fluid Mechanics*, Vol. 56, Nov. 1972, pp. 143-160.

[25]*Proceedings of a Workshop Sponsored by Project Squid*, Purdue University, 1972.

[26]Catalano, G. D., Morton, J. B., and Humphris, R. R., "Experimental Investigation of an Axisymmetric Jet in a Coflowing Airstream," *AIAA Journal*, Vol. 14, Sept. 1976, pp. 1157-1158.

[27]Gad-el-Hak, M., Morton, J. B., and Humphris, R. R., "An Investigation of Turbulent Diffusion," RLES Rept. No. ESS-3837-102-79, University of Virginia, 1975.

[28]Tennekes, H. and Lumley, J. L., *A First Course in Turbulence*, MIT Press, Cambridge, Mass., 1972.